Comparison of Estimates of First-Year Dairy Manure Nitrogen Availability or Recovery Using Nitrogen-15 and Other Techniques

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ABSTRACT

Measurements of dairy manure nutrient availability to crops typically show great variability. Approaches that are more accurate are needed to improve manure management and reduce nutrient loss to the environment. In this study, we compared direct (^{15}N recovery) and indirect (difference method [Diff Meth] and fertilizer equivalence [FE] approach) methods of determining first-year dairy manure N availability or recovery during three cropping seasons. A field experiment was conducted on a Plano silt loam (fine-silty, mixed, superactive, mesic Typic Argiudolls) planted to corn (*Zea mays* L.). Plots received either manure, fertilizer N, or no N. Microplots receiving ^{15}N-labeled manure were also established each study year. Manure was applied to a new plot each cropping season. Whole-plant N uptake was the best crop parameter to use for FE estimates. Estimates of N availability by relative effectiveness (Rel Eff), which are derived from the Diff Meth, and FE were similar (32 and 41%, respectively) and higher than unlabeled N or ^{15}N recovery measurements because these indices factor in N use efficiency. Measures of the Rel Eff of manure N use were highly affected by control plot N uptake. The FE approach is less influenced by control plots, but it requires the inclusion of several more treatments and use of mathematical functions to describe crop response to N. These limitations are reflected in the wide ranges obtained for N availability estimates (-60 to 148%). Although apparent N recovery by the Diff Meth (14%) or direct measurements of ^{15}N recovery (16%) were close on average, variability tended to be much lower for the ^{15}N method. In addition, the Diff Meth was highly dependent on initial soil conditions. Use of ^{15}N-labeled manure, although more costly and time-consuming, provided more consistent and reliable results.

Animal manures are valuable sources of crop nutrients and organic matter, which can improve soil physical conditions. However, when inorganic fertilizers became available at relatively low cost, they began to be used extensively, and manure was considered more of a waste than a resource. Fertilizers have a guaranteed nutrient content and are readily available, while manures vary widely in composition and the nutrients in the organic fraction must be mineralized to become plant-available. The difficulty of accurately predicting availability of manure nutrients to crops renders it a somewhat uncertain crop nutrient source. Farmers often acknowledge the beneficial effects of manure on soil quality and nutrient levels; however, in spite of the economic benefits, many do not credit these nutrients (Nowak et al., 1998).

Over the past 10 to 15 yr, there has been an increasing effort to improve the use of manure as a crop nutrient source for both environmental and economical reasons. Optimal manure N use that ensures adequate crop nutrition while avoiding pollution problems requires accurate and reliable estimates of manure N availability or recovery by the crop during the growing season. Several relatively simple chemical and biological indices have been proposed to predict N availability from native soil organic matter or organic amendments (Waring and Bremner, 1964; Stanford and Smith, 1972; Hong et al., 1990; Serna and Pomares, 1991; Paul and Beauchamp, 1993; Qafoku et al., 2001). However, it is widely acknowledged that these are more useful to compare relative availabilities than to provide absolute numbers (Keeney, 1982; Douglas and Magdoff, 1991). In addition, it is not likely that satisfactory fertilizer recommendations can be based on a single index (Bundy and Meisinger, 1994), and ultimately these predictions have to be corroborated by field experiments.

Two commonly used methods to determine manure N availability to crops are the fertilizer equivalence (FE) approach and measurement of apparent N recovery by the difference method (Diff Meth). The results from these indirect methods are often highly variable. For example, Motavalli et al. (1989), using the FE approach, measured 12 to 63% of dairy manure N as plant-available during the first season after application. Other estimates for dairy manure N availability have ranged from 10 to 57% (Castellanos and Pratt, 1981; Safley et al., 1986; Xie and MacKenzie, 1986; Jokela, 1992; Paul and Beauchamp, 1993).

Nitrogen recovery is the amount of applied N actually taken up by the plant and typically measured in aboveground tissue. Nitrogen availability is the amount of applied N that could be taken up by the plant in forms, concentrations, and locations that allow utilization by plants (Bundy and Meisinger, 1994), or compounds likely to convert to chemical forms accessible to plant roots during the growing season (Blackmer, 2000). The two indices of N availability used in this study compare manure N use by the crop to the use of fertilizer N, which is considered to be 100% plant-available. Hence, in this paper, available N can be thought of as N that behaves as fertilizer N, and therefore might be termed fertilizer N replacement value.

A direct assessment of manure N recovery can be attained by labeling manure with ^{15}N and then measur-

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Abbreviations: Diff Meth, difference method; FE, fertilizer equivalence; GNU, grain nitrogen uptake; GY, grain yield; Rel Eff, relative effectiveness; TKN, total Kjeldahl nitrogen; WPNU, whole-plant nitrogen uptake; WPY, whole-plant yield.

ing ^{15}N in the crop (Kirchmann, 1990; Sørensen et al., 1994), but an estimate of availability also requires consideration of N recovery from ^{15}N-enriched inorganic fertilizer. It is frequently assumed that the inorganic portion of manure N is as available as fertilizer N. However, Paul and Beauchamp (1995) found it to be about 59% as available as fertilizer N due to greater losses by NH_3 volatilization, denitrification, and immobilization. We chose to refer N availability and recovery to total N in manure, to allow these losses to be reflected in the indices.

The objective of this research was to compare estimates of dairy manure N availability or recovery by corn using direct (^{15}N labeled manure) and indirect (Diff Meth and FE) techniques in a field study.

MATERIALS AND METHODS

Experiment Layout and Sampling

A field trial was conducted from 1998 to 2000 at the West Madison Agricultural Research Station in Madison, WI (45°05′ N, 89°31′ W) on a Plano silt loam. Average pre-experiment plow layer (0–15 cm) soil tests results, based on two samples per block, were: pH in water (soil to water ratio of 1.3:1), 6.7; organic matter by loss on ignition, 41 g kg^{-1}; Bray P$_1$, 50 mg kg^{-1}; Bray K, 146 mg kg^{-1}; total N in the top 30 cm of soil, 2026 mg kg^{-1}; NH$_4^+$–N, 14 mg kg^{-1}; and NO$_3^-$–N, 8.2 mg kg^{-1} (Combs et al., 2001). The field was in alfalfa (*Medicago sativa* L.) from 1994 to 1996, and in corn in 1997. No manure had been applied for at least 4 yr before the start of the trial. Although the site chosen for the study had a relatively high fertility, it may represent many common scenarios for dairy farmers who apply manure periodically to their fields (Nowak et al., 1998).

Treatments were five levels of fertilizer N (45, 90, 135, 179, and 224 kg ha^{-1}, applied as NH$_4$NO$_3$), two manure rates (estimated to provide approximately 90 and 180 kg available N ha^{-1} to corn the first year following application based on 40% availability), and a control receiving neither fertilizer N nor manure. There was a minimum of four replications of each treatment, arranged in four blocks to account for variations due to field topography. The plots were 10.6 by 6 m and separated by 1.5-m alleys, and contained eight corn rows, 0.75 m apart. For the ^{15}N experiment, microplots of 1.5 by 2.3 m containing three corn rows were established within each of the low manure rate plots, following the design proposed by Jokela and Randall (1987).

Fertilizer and manure were applied about 5 d before planting. The field was disked twice (12–14 cm deep) within 3 to 20 h after application to incorporate the manure. All plots were planted to corn (cv. Lemke 6063) in each of the three study years. To ensure an adequate supply of P and K and optimize plant growth (Motavalli et al., 1993), all plots received starter fertilizer (band-applied, 5 cm to the side and 5 cm below the seed at planting, at 224 kg ha^{-1} of 9–23–30 in 1998 and 1999, and 168 kg ha^{-1} in 2000). About 40 d after planting, plants were thinned to a uniform population of 55 000, 74 000, and 60 000 plants ha^{-1} in 1998, 1999, and 2000, respectively. The target population was 74 000 plants ha^{-1}, but poor seeding in 1998 and soil crusting in 2000 resulted in lower than optimal stands. The field received herbicides at (or shortly following) planting each year, and was cultivated at least once each season.

Corn aboveground tissue (henceforth referred to as "whole-plant") was harvested at approximately physiological maturity by cutting 10 adjacent plants 5 cm above the ground from one row in 1998 and 1999, and five from each of three rows (15 total) in 2000. The harvesting procedure was changed to obtain a more representative sample and reduce variability between replications of the same treatment. Grain was harvested from two entire rows (10.6 m) with a small plot combine. Three plants were cut from the middle row of each of the ^{15}N microplots. Whole-plant and grain subsamples were oven-dried (55°C, 5–10 d) to determine tissue dry matter, ground in a stainless steel Wiley mill to pass a 2-mm screen, and stored in plastic bags until analyzed for total Kjeldahl nitrogen (TKN). Samples from the ^{15}N microplots were reground in a Udy mill to pass a 1-mm screen, and analyzed for ^{15}N and total N. Since samples from ^{15}N microplots were very small, the more representative main plot data were used for whole-plant yield calculations in both main and microplots. Whole-plant yields are reported on a dry-matter basis, whereas grain yields are at 15.5% moisture. After sampling, the remaining plants were removed from the field. The site was chisel-plowed each fall.

Treatment Applications

Each rate of NH$_4$NO$_3$ was broadcast preplant to the same plots each year. Although some residual effect might be expected, this was not obvious in our experiment, as crop response slopes did not increase with time. Manure was applied to a new plot each year. The number of control plots diminished with time (e.g., plots receiving manure in 1999 for the first time were controls in 1998), but there was always at least one control per replication. The number of plots receiving manure was also different every year because this study used a subset of plots within a larger study. However, only plots receiving manure for the first time, with no other amendments applied since the onset of the experiment, were evaluated.

Fresh dairy manure (composite of feces, urine, and straw bedding) was collected from a stockpile where it had been stored for a few days. In 1998 and 1999, manure was applied with a small spreader. The amount applied was calculated by placing a small tarpaulin over the area where the ^{15}N was to be applied. After spreading, the tarpaulins were removed and weighed, and a subsample of the manure was frozen until analyzed. To increase precision, in 2000, manure for each plot was individually weighed and uniformly forked on the plot. Manure analyses, as well as amounts applied each year, are presented in Table 1.

Manure enriched with ^{15}N was hand-applied to each microplot at rates approximately equal to, and following the same schedule as, the main plot. Each year, manure was labeled following the procedure described by Powell and Wu (1999), where field-grown corn and alfalfa had been supplied with ^{15}N-enriched ammonium sulfate the preceding year. The resulting silage and hay were fed to two nonlactating cows (*Bos taurus*). Feces and urine were collected separately to allow the proportionate combination of feces from excretion periods before and after peak fecal ^{15}N concentrations. This was necessary to obtain feces having uniformly labeled microbial and undigested feed N components (Powell and Wu, 1999). Oat straw (not ^{15}N-enriched) was used as a bedding source. Each year, a mixture of 11.7 kg feces, 8.1 kg urine, and 2.3 kg straw per microplot was applied. Manure atom %^{15}N (average atom %^{15}N in feces and urine, weighed by N content) was 1.47, 1.12, and 1.44 in 1998 to 2000, respectively.

Chemical Analyses

Manure was analyzed following the procedures outlined by Combs et al. (2001). Total N in plant tissue was determined

Table 1. Chemical analyses and rates of dairy manure applied to experimental plots.†

Year	Dry matter		Total N‡		NH₄⁺–N‡		Manure rate			Total N rate		
	^{15}N	Unl	^{15}N	Unl	^{15}N	Unl	^{15}N	L	H	^{15}N	L	H
	——————————— g kg^{-1} ———————————						——— Mg ha^{-1} ———			——— kg ha^{-1} ———		
1998	170	210	20	26	5	8	63	35	70	224	194	388
1999	170	260	26	25	7	7	63	38	77	284	250	501
2000	170	240	21	30	6	10	63	34	68	235	233	489

† ^{15}N, ^{15}N-enriched manure; Unl, unlabeled manure; L, low rate (unlabeled manure); H, high rate (unlabeled manure).
‡ Dry-matter basis.

following a semimicro Kjeldahl digestion procedure adapted from Liegel et al. (1980). The digestions were performed on 250 mg of plant tissue in Pyrex Folin-Wu tubes. The digests were diluted, filtered, and analyzed for NH_4^+–N in an automated colorimeter (Lachat Instruments, Milwaukee, WI) using QuikChem Method 13-107-06-2-D (Lachat Instruments, 1992) with sodium phenate and 5.2% sodium hypochlorite. Total N and ^{15}N concentrations in dairy feces, urine, and corn tissue samples from ^{15}N microplots were determined using a Carlo Erba (Milan, Italy) elemental analyzer coupled with a mass spectrometer (Europa [Crewe, UK] 20/20 tracermass) on 5-mg samples.

Nitrogen Availability and Recovery Calculations

Corn grain nitrogen uptake (GNU) and whole-plant nitrogen uptake (WPNU) were determined by multiplying dry matter yields by respective tissue N concentrations. Since a small amount of N (15–20 kg ha^{-1}) in starter fertilizer was consistently applied to all plots (including controls), this amount was not considered in the amounts of applied N. Manure N availability or recovery was estimated using three methods.

Fertilizer Equivalence

The FE method compares crop yield or N uptake in the manure treatments with those obtained from inorganic N fertilizer. Four crop parameters were used: whole-plant yield (WPY), WPNU, grain yield (GY), and GNU. Each year, each crop parameter was regressed against fertilizer N rate. These relationships were best described by linear functions in all cases, except for WPY and WPNU in 1999, where data were best-fit to an asymptotic response model adapted from Klausner and Guest (1981):

$$Y = A - B \exp(-Cx) \quad [1]$$

where Y = crop response (Mg ha^{-1} for yield, and kg ha^{-1} for N uptake), A = maximum crop response attainable, B = difference between A and crop response in the unfertilized control, C = constant, and x = fertilizer rate (kg N ha^{-1}).

To solve for FE for each crop parameter, data from manured plots were entered into the regression curves, and the fertilizer rate that would have produced the same yield or N uptake (the FE) was determined. This process is graphically illustrated in Fig. 1, although FEs were calculated numerically. Fertilizer equivalents for replications of a given treatment were averaged. Percent nitrogen availability (NA) was calculated by dividing the FE by total applied manure N:

$$NA\ (\%) = \frac{FE}{applied\ manure\ N} \times 100 \quad [2]$$

Difference Method

The Diff Meth assumes that the soil provides the same amount of N to all plots and that all crop N uptake in the

amended (manure or fertilizer) plots in excess of control N uptake was the result of the treatment. Apparent N recovery is given by:

$$apparent\ N\ recovery\ (\%) =$$
$$\frac{treatment\ N\ uptake - control\ N\ uptake}{applied\ N} \times 100 \quad [3]$$

In the above equation, treatment N uptake and control N uptake were the N (kg ha^{-1}) contained in the aboveground whole-plant for a given treatment and control plots, respectively. Applied N is the total rate of N applied in the treatment plot (kg ha^{-1}). Calculations were made for each individual plot using the mean control N uptake for that year.

Apparent recovery of manure N can be compared with that of a fertilizer treatment providing an approximately similar amount of expected available N. An index of manure N availability termed "relative effectiveness" estimates the proportion of manure N that behaves as fertilizer N and therefore is more comparable with results from the FE method:

$$Rel\ Eff\ (\%) =$$
$$\frac{apparent\ N\ recovery\ (manure\ treatment)}{apparent\ N\ recovery\ (fertilizer\ treatment)} \times 100 \quad [4]$$

The fertilizer treatments chosen were 90 kg N ha^{-1} rate for the low manure rate and 179 kg N ha^{-1} for the high manure rate, under the assumption that approximately 40% of newly applied manure N would be available during the first growing
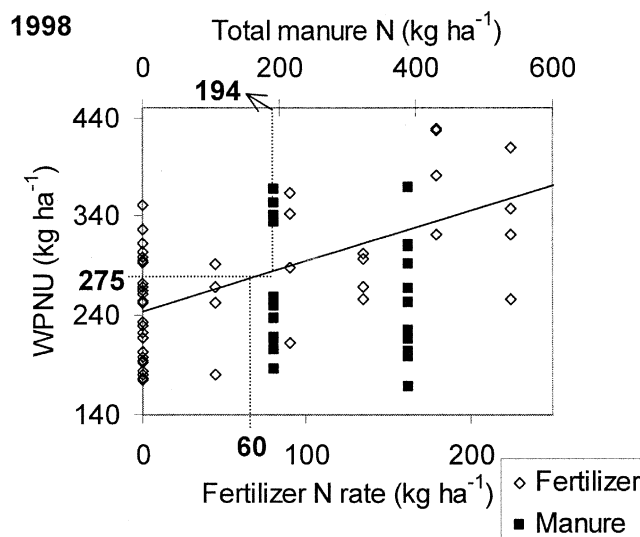
Fig. 1. Corn whole-plant nitrogen uptake (WPNU) at various fertilizer and manure N rates after initial manure applications, 1998. Solid line represents the regression ($p < 0.001$) of WPNU against fertilizer N rate (primary x axis). Secondary x axis shows manure N rate. Dashed lines and bold numbers illustrate the calculation of fertilizer equivalents.

Table 2. Corn whole-plant and grain yields.

Treatment	N rate	1998		1999		2000	
		Whole-plant†	Grain‡	Whole-plant	Grain	Whole-plant	Grain
	kg ha^{-1}			Mg ha^{-1}			
Control	0	21.5	11.6	18.8	11.2	18.1	8.5
Fertilizer	45	21.8	12.0	20.7	10.9	16.7	9.4
	90	25.2	13.3	20.7	12.3	20.1	9.7
	135	25.2	12.7	22.4	12.2	19.3	10.7
	179	29.9	12.5	21.6	12.7	19.6	10.7
	224	26.7	13.3	21.1	12.8	21.4	11.0
Manure§	226	23.1	12.1	20.5	11.5	20.2	9.6
	459	23.0	13.8	20.1	13.0	17.6	9.4

† Dry matter at physiological maturity.
‡ Reported at 15.5% moisture.
§ Rate is 3-yr average of total N applied.

season. Although blocking did account for some variation, it actually increased variability of Rel Eff values, probably because there was only one plot per fertilizer rate per block. Mean apparent N recovery for any given treatment was the same with or without blocking; therefore, the mean N uptake for each fertilizer rate and controls was used.

Nitrogen-15 Recovery

Manure N recovery was estimated directly by measuring percentage ^{15}N recovered in aboveground corn tissue at physiological maturity using the procedures outlined by Hauck and Bremner (1976):

$$^{15}\text{N recovery (\%)} = \frac{P(c - d)}{f(a - b)} \times 100 \qquad [5]$$

In this equation, P = total crop N uptake (yield data from main plot, N concentration from microplot), f = total manure N applied, a = atom % ^{15}N in the manure applied, b = atom % ^{15}N in the unlabeled manure (0.377 in 1998, and 0.366 in 1999 and 2000), c = atom % ^{15}N in the treated crop, and d = atom % ^{15}N in the control crop (0.366).

Statistical Analysis

Statistical analyses and regressions were performed using SAS (SAS Institute, 1990). Each crop parameter was analyzed as a randomized complete block design, with treatments and years as fixed effects. Blocks (replications) were treated as random effects. The same approach was used to analyze N availability and recovery estimates. For FE, the fixed effects considered were year, rate, and crop parameter; for the Diff Meth (both apparent N recovery and Rel Eff), year and rate; for ^{15}N recovery, year; and for the comparisons among methods, year and method.

Type III F tests were used to assess the significance of fixed effects. Whenever interactions among fixed effects were not

significant, they were eliminated from the model to gain degrees of freedom for the error term. When fixed effects were significant at α = 0.10, selected orthogonal contrasts were performed to compare treatment means. The contrast labeled "manure vs. control" compared mean crop response in manured plots (both high and low rates) against control. The contrast labeled "fertilizer linear increase" assessed a linear increase in crop response to fertilizer N rates.

Regression analyses were performed by year for each crop parameter to determine crop response to fertilizer. Linear, quadratic plateau, and exponential models were used. For nonlinear regressions, the endpoint for successive iterations was determined using the Marquardt method (SAS Institute, 1990). The required initial values were estimated based on the graphs of crop response versus fertilizer rate. Single plot observations rather than averages by treatments were used to obtain the curves. The best model was chosen based on the highest R^2, but whenever the inclusion of additional parameters did not result in a substantially better fit, the simpler model was used.

RESULTS AND DISCUSSION

Yields and Nitrogen Uptake

Tables 2 and 3 show that crop responses to applied manure and fertilizer were generally higher in 1998 and tended to decrease thereafter. Average WPY, GY, and GNU were significantly different for all study years (Table 4). Average WPNU in 1998 was significantly greater than in 1999 and 2000 (Table 4).

The relatively higher crop yield and N uptake in 1998 was probably due to high initial soil fertility (N and organic matter levels) and the rotational benefit from the 1996 alfalfa crop. The positive effects of alfalfa in the rotation may extend for at least two years (Voss

Table 3. Corn whole-plant and grain N uptake.

Treatment	N rate	1998		1999		2000	
		Whole-plant	Grain	Whole-plant	Grain	Whole-plant	Grain
		kg ha^{-1}					
Control	0	246	143	166	126	185	86
Fertilizer	45	248	147	202	121	166	96
	90	301	166	222	137	210	89
	135	280	155	229	138	200	114
	179	390	183	236	156	217	113
	224	333	188	243	153	269	128
Manure†	226	275	152	210	130	224	101
	459	260	161	218	155	204	97

† Rate is 3-yr average of total N applied.

Table 4. Effect of treatments and year of application on corn whole-plant yield (WPY), grain yield (GY), whole-plant nitrogen uptake (WPNU), and grain nitrogen uptake (GNU).

	p Value			
	WPY	GY	WPNU	GNU
Effect				
Treatment	<0.001	<0.001	<0.001	<0.001
Year	<0.001	<0.001	<0.001	<0.001
Contrast				
1998 vs. 1999	<0.001	0.007	<0.001	<0.001
1998 vs. 2000	<0.001	<0.001	<0.001	<0.001
1999 vs. 2000	0.007	<0.001	0.520	<0.001
Manure vs. control	0.007	<0.001	<0.001	<0.001
Manure high vs. control	0.072	<0.001	0.013	<0.001
Manure low vs. control	0.008	0.086	0.001	0.052
Manure high vs. manure low	0.443	<0.001	0.523	0.012
Fertilizer linear increase	<0.001	<0.001	<0.001	<0.001

and Shrader, 1984; Fox and Piekielek, 1988). In addition, precipitation was somewhat more evenly distributed in 1998 (data not shown). In 2000, there was only 14.2 mm of rain for the 16 d following planting. On Day 17, the highest precipitation event of the season (79.2 mm) occurred with heavy hail damaging plant tissue. This event caused substantial runoff in some sectors of the field, even washing away many young plants. The reduced stand, potential loss of nutrients in runoff, and wet soil conditions until mid-June (probably reducing N mineralization and increasing denitrification) were probable causes for overall lower yields and N uptake in 2000 than other study years.

Over all three years of the study, there was a significant trend toward a linear increase in corn yield and N uptake with fertilizer rate (Table 4). Average crop responses were significantly higher in manure-amended than control plots (Table 4), and in general, crop responses to manure were about the same as those obtained for fertilizer between N application rates of 45 and 90 kg ha^{-1} (Tables 2 and 3). There was strong evidence that manure at the high rate increased the whole-plant and grain yield and N uptake compared with the control; however, this increase for the low manure rate was less distinct (Table 4). Crop differences between the high and low manure rates were only evident for the grain parameters (GY and GNU) (Table 4). Tables 2 and 3 show that whole-plant responses were similar for both manure rates, and sometimes slightly lower for the high manure rate. Motavalli et al. (1989) found similar or slightly lower corn silage yields for one of the six site-years at high dairy manure rates (about 150 Mg manure ha^{-1}) compared with a moderate rate (90 Mg manure ha^{-1}), although rates were higher than the ones used in the present experiment. Safley et al. (1986) and Vitosh et al. (1973) similarly reported little if any additional benefit from high rates of applied manure.

For this field, in these years, manure applied at the lower rate appeared to have provided sufficient N to the crop. The small increase in crop responses that resulted from doubling the manure rate generally did not justify the increased inputs.

Manure Nitrogen Availability and Recovery

Fertilizer Equivalence

Regressions for each crop parameter against fertilizer rate and the corresponding FE calculations were made by year because of the great across-year variation observed in crop responses. Large variability was also observed within a year (Fig. 1). This was probably due to the large field size (0.7 ha) with uneven slope and soil characteristics. We tried to reduce variability by blocking, but evaluating manure versus fertilizer responses within a block still showed considerable variation. In the end, we found it was more satisfactory to use one response curve for the whole field. The regression coefficients, R^2, and p values are presented in Table 5. As an example of FE calculations, in 1998, the average WPNU was 275 kg ha^{-1} (Fig. 1) at the low manure rate (194 kg N ha^{-1}). According to the regression line, a fertilizer rate of 60 kg ha^{-1} would have resulted in the same crop response; this is the FE for this manure rate. Using Eq. [2]: N availability % = (60 kg ha^{-1}/194 kg ha^{-1}) × 100 = 31%. This means that manure N (applied at 194 kg ha^{-1}) had approximately 31% the effect of fertilizer N in increasing WPNU.

Estimates of first-year manure N availability by the FE method, based on WPY, GY, WPNU, and GNU, are given in Table 6. For the low manure rate, N availability values based on the different crop parameters ranged from 17 to 75%. The overall mean across years and crop parameters was 32%. At the high manure rate, manure N availability ranged from 2 to 76% with an overall mean of 26%. Motavalli et al. (1989) reported an average dairy manure N availability of 32%, based on WPNU FE across six site-years and three manure rates providing from about 84 to 274 kg ha^{-1} of available N. Our average FE based on WPNU across years and rates is somewhat lower (26%). First-year dairy manure N availabilities of 27 and 26% have been reported by Jokela (1992) based on WPY and WPNU, respectively. Our estimations are slightly higher (34 and 41%, respectively) at a similar manure N rate (they used average N inputs of 240 kg ha^{-1}). Other reported dairy manure N availability estimates are 33 to 60% (Beauchamp, 1983), 25 to 100% (Xie and MacKenzie, 1986), and 42% (Klausner and Guest, 1981). These studies show that while average diary manure availabilities appear similar across a wide range of soil fertility and environmental conditions, substantial variation within a study can be observed.

Statistical comparison of FE first-year manure N availability estimates only showed significance for the interaction of manure rate × crop parameter (i.e., WPY, GY, WPNU, and GNU) at $p = 0.008$, and year × rate at $p = 0.046$. These significant interactions seemed to be due to the wide variability in crop responses inherent to any field experiment, rather than the result of any meaningful trend.

In all years, N availability estimates were lower for the high than the low manure rate, using WPY ($p = 0.026$) or WPNU ($p = 0.008$). In 2000, all estimates were lower for the high manure rate ($p = 0.010$). This

Table 5. Regression equations fitted to various corn responses (Y) vs. fertilizer N rate (X).

Year	Parameter†	n‡	Equation	R^2	p Value
1998	GNU	48	$Y = 142.61 + 0.1942X$	0.361	<0.001
1999	GNU	32	$Y = 123.65 + 0.1462X$	0.331	<0.001
2000	GNU	24	$Y = 83.731 + 0.183X$	0.408	0.001
1998	GY	48	$Y = 11.72 + 0.00697X$	0.153	0.006
1999	GY	32	$Y = 11.147 + 0.00792X$	0.234	0.005
2000	GY	24	$Y = 8.735 + 0.0109X$	0.354	0.003
1998	WPNU	48	$Y = 244.59 + 0.5063X$	0.366	<0.001
1999	WPNU	32	$Y = 244.55 - 78.675 \exp(-0.0135X)$	0.533	<0.001
2000	WPNU	24	$Y = 167.71 + 0.3558X$	0.479	<0.001
1998	WPY	48	$Y = 21.46 + 0.0321X$	0.392	<0.001
1999	WPY	32	$Y = 21.614 - 2.843 \exp(-0.0238X)$	0.246	0.017
2000	WPY	24	$Y = 17.455 + 0.0155X$	0.255	0.012

† GNU, grain nitrogen uptake; GY, grain yield; WPNU, whole-plant nitrogen uptake; WPY, whole-plant yield.
‡ Number of points (single plot observations) in the regression.

was the consequence of small (if any) increases in crop responses after doubling the manure rate (Eq. [2]). Although not significant, it is noteworthy that N availability based on GY in 1998, and GY and GNU in 1999, was higher at the high than the low manure rate.

At the low manure rate, N availability estimates obtained in 2000 were higher than in 1998 ($p = 0.045$) and 1999 ($p = 0.040$). This was possibly due to a gradual lowering of the soil N supply and a reduced influence of the previous alfalfa crop. As a result, corn probably had to rely more heavily on the fertilizer or manure N inputs. Control plot yields and N uptake decreased significantly (statistics not shown) with time.

Evaluation of the various availability estimates using the different crop response parameters showed that care must be exercised when choosing a crop parameter to calculate these estimates. Grain yield and GNU sometimes appeared to be more sensitive indicators of crop response by giving more statistically significant treatment differences (Table 4), but their response curves (vs. fertilizer rate) resulted in less steep slopes compared with WPY or WPNU (Table 5). When the slope is shallow, a given change in the y axis (the crop response measured) translates into a much greater uncertainty in the x axis (the FE calculated). In general, this study showed that the steepest slopes and highest R^2 and p values were found for WPNU. Other reasons to choose this parameter over the others as an indicator of manure

Table 6. First-year manure N availability according to the fertilizer equivalence approach, using various crop parameters.†

Year	Manure rate	WPY	GY	WPNU	GNU
	kg ha^{-1}		%		
1998	194	26 (15.0)‡	30 (26.0)	31 (19.5)	25 (14.9)
	388	12 (8.9)	76 (14.9)	8 (8.8)	25 (8.9)
	mean§	19 (8.6)	53 (15.5)	19 (10.7)	25 (8.5)
1999	250	21 (11.7)	19 (18.0)	43 (18.0)	17 (12.7)
	501	6 (3.3)	46 (11.7)	9 (3.0)	43 (7.9)
	mean§	13 (5.9)	32 (11.0)	28 (11.1)	30 (8.0)
2000	233	75 (35.9)	35 (34.5)	68 (27.5)	40 (17.2)
	489	2 (10.3)	12 (13.1)	21 (11.4)	14 (7.9)
	mean§	38 (22.2)	24 (17.6)	45 (16.4)	27 (10.0)
Mean¶	226	34 (11.2)	27 (14.9)	41 (12.2)	25 (8.9)
	459	8 (5.0)	56 (9.8)	10 (5.2)	29 (5.6)
	mean§	21 (6.3)	41 (9.1)	26 (7.1)	27 (5.2)

† GNU, grain nitrogen uptake; GY, grain yield; WPNU, whole-plant nitrogen uptake; WPY, whole-plant yield.
‡ Standard errors are given in parentheses.
§ Mean fertilizer equivalent, across manure rates.
¶ Mean fertilizer equivalent, across years, weighed by number of observations.

N availability include (i) the limited increase in dry matter production as a result of additional N at high N inputs, whereas crop N uptake can still increase further (Klausner et al., 1994); (ii) the fact that N in the grain not only depends on the total amount of crop N uptake, but also on redistribution of N from vegetative tissue to grain, which might vary from one season to the next; and (iii) the fact that grain yield is highly affected by weather during anthesis, while N uptake is a cumulative parameter integrated over the entire cropping season (Meisinger, 1984). As was confirmed by this study, WPNU is the most reliable crop parameter to analyze crop response to N.

Difference Method

According to this method, the amount of N provided by manure or fertilizer was equaled to additional crop N uptake with respect to the control, and referenced to the total N applied (Eq. [3]). As discussed previously, an N availability index (Rel Eff) can be obtained by relating the apparent N recovery from the manure treatments to apparent recovery from an approximately similar fertilizer rate (Eq. [4]). Both indices for first-year manure and fertilizer treatments are presented in Table 7. Neither apparent N recovery nor Rel Eff of manure N varied significantly across years.

On average, from 15 to 18% of the total manure N applied at the low manure rate was apparently recovered in the aboveground portion of the crop, with a weighed average of 16% across years. This is in good agreement with previous estimates of 19% at similar manure rates (Motavalli et al., 1989) and 16.2% for liquid dairy manure and 10.5% for solid beef cattle manure, averaged across rates of 100, 200, and 300 kg N ha^{-1} (Paul and Beauchamp, 1993). Jokela (1992) measured a much higher (35%) apparent N recovery for manure applied for the first time, but the controls in this trial were severely N deficient, with probably poorly developed roots leading to overestimation of the manure N effect. Apparent N recovery at the high manure rate ranged from 4 to 10% with a mean of 6%, significantly lower ($p = 0.087$) than mean N recovery at the low manure application rate. This was expected, since total applied N increased by a large amount, whereas plant uptake did not increase as much. Other authors have reported decreasing apparent N recovery with in-

Table 7. First-year apparent manure nitrogen recoveries (ANR) and relative effectiveness (Rel Eff) of manure according to the difference method for whole-plant N uptake.

Manure N†	1998		1999		2000		Mean‡	
	ANR	Rel Eff	ANR	Rel Eff	ANR	Rel Eff	ANR	Rel Eff
kg ha^{-1}				%				
226	15 (9.9)§	24 (16.1)	18 (3.1)	28 (4.9)	17 (9.8)	61 (35.2)	16 (5.1)	32 (9.9)
459	4 (4.4)	4 (5.6)	10 (3.1)	27 (7.9)	4 (4.1)	22 (23.0)	6 (2.5)	15 (5.5)
Mean¶	9 (5.4)	14 (8.6)	14 (2.3)	27 (4.5)	10 (5.5)	41 (20.8)	11 (2.9)	23 (5.7)

† Rate is 3-yr average of total N applied.
‡ Across years, weighed by number of observations.
§ Standard errors are given in parentheses.
¶ Across manure rates.

creasing N rate (Hensler et al., 1970; Culley et al., 1981; Motavalli et al., 1989).

Manure N availability as estimated by Rel Eff at the low manure rate ranged from 24 to 61% with an average of 32%. This means that manure N was approximately 32% as effective as a similar rate of fertilizer N in increasing crop N uptake. Consistently lower estimates, although not significant ($p = 0.14$), were obtained at the high manure rate, which ranged from 4 to 27%, with a mean of 15%. Again, these results were a consequence of the small increase in crop N uptake after doubling the manure rate.

Nitrogen-15 Recovery

First-year recoveries of ^{15}N in whole-plant (Eq. [5]) ranged from 10 to 22%, with an average across years of 14% (Table 8). These results are somewhat lower than those from other ^{15}N experiments using sheep manure and barley as a crop, with ^{15}N recoveries of 12 to 14% when feces only were applied (Sørensen et al., 1994), 22% (Jensen et al., 1999) (undersown with ryegrass), and 22% (Thomsen et al., 1997). Ryegrass amended with labeled fresh chicken manure recovered 26% (Kirchmann, 1990). These experiments were performed in pots or lysimeters where the manure was immediately covered with soil. Reduced N losses and possibly differences in type of manure and crop and soil conditions are likely causes of the higher ^{15}N recoveries.

In our experiment, ^{15}N recovery in 1998 (10%) was significantly lower than in 1999 (17%, $p = 0.052$) and 2000 (22%, $p = 0.011$). One possible reason for this trend might have been the high initial soil fertility of the experimental site. Another influencing factor was probably reduced NH$_3$ volatilization in 1999 and 2000. In 1998, manure was incorporated about 20 h after being applied, whereas in 1999 and 2000, incorporation was done within 3 h. Several researchers have shown that dairy manure N volatilization losses can be very high in the first few hours after application (Heck, 1931; Lauer et al., 1976; Sanderson and Jones, 1997).

Comparison of Methods

Table 8 shows the N availability and recovery estimates according to the FE, difference, and ^{15}N methods for each year. The ranges were usually quite large, especially for the FE and Diff Meth; however, to compare the indices, we averaged them. Only the low manure rate was considered, since this was the only level of application common to all three methods. Only results based on WPNU were taken into account for the FE method, since both the ^{15}N and the Diff Meth were based on this crop parameter. Apparent N recovery by the Diff Meth and ^{15}N recovery are estimates of the percent of manure N that is actually taken up by the corn. On the other hand, the FE and Rel Eff methods estimate available N from manure in comparison with fertilizer N use, or potentially utilizable by the crop. An estimate of manure N availability by the ^{15}N method could have been obtained by including ^{15}N-enriched fertilizer treatments and following a similar procedure to that of the FE method or computing a Rel Eff; however, those treatments were not included in the early years of this experiment.

Estimates of N recovery were not significantly affected by method or year. However, ranges for ^{15}N recovery were somewhat narrower than for the Diff Meth, particularly in 1998. More importantly, several of the N recoveries as computed by the Diff Meth were negative (more commonly in 1998), meaning that crop N uptake in control plots exceeded those in manured plots. If

Table 8. Estimates of first-year manure N availability and recovery using various methods, for the low manure rate.

Year	n†	N recovery				N availability			
		^{15}N recovery		Apparent recovery‡		Rel Eff‡		FE (WPNU)§	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range
					%				
1998	12	10	4 to 15	15	−31 to 62	24	−51 to 100	31	−60 to 124
1999	8	17	8 to 26	18	9 to 31	28	15 to 49	43	10 to 148
2000	4	22	7 to 42	17	−4 to 43	61	−14 to 156	68	−10 to 142
Mean¶		14		16		32		41	

† Number of observations.
‡ According to the difference method (Diff Meth). Rel Eff, relative effectiveness.
§ FE, fertilizer equivalence; WPNU, whole-plant nitrogen uptake.
¶ Across years, weighed by number of observations.

during 1998 native N levels were high due to the previous alfalfa, then it is reasonable that no extra N was needed. However, some dairy farmers are faced with the need to dispose of manure wherever possible. Whereas the credit given to previous alfalfa is high the first year (110–215 kg ha^{-1}), this is much smaller the second year (Voss and Shrader, 1984).

A comparison between Rel Eff and FE manure N availability estimates showed that the two methods did not statistically differ, and year also had no effect. Estimates of N availability by both methods were remarkably close at both manure rates (except in 1999; Tables 6 and 7) and averaged across rates: 19, 28, and 45% (FE, 1998–2000; Table 6) versus 14, 27, and 41% (Rel Eff, 1998–2000; Table 7). This was probably because both these methods estimate the proportion of manure N that behaves as fertilizer N, using slightly different approaches. The Rel Eff estimate of N availability uses actual measurements of N uptake in control, manure, and fertilizer (at a comparable rate) plots. Combining Eq. [3] and [4]:

$$\text{Rel Eff (\%)} = \frac{(\text{manure N uptake} - \text{control N uptake})}{(\text{fertilizer N uptake} - \text{control N uptake})} \times \frac{\text{apparent fertilizer N}}{\text{apparent manure N}} \times 100 \quad [6]$$

Nitrogen availability by the FE method can be expressed in a similar way:

$$\text{NA (\%)} = \frac{(\text{manure N uptake} - \text{control N uptake})_{regr}}{(\text{fertilizer N uptake} - \text{control N uptake})_{regr}} \times \frac{\text{apparent fertilizer N}}{\text{apparent manure N}} \times 100 \quad [7]$$

where the subscript regr denotes values that are interpolated from the regression curves. Applied fertilizer N is the fertilizer rate that would have produced the same N uptake as the manure treatment (i.e., it is the FE). This also implies that manure N uptake = fertilizer N uptake; therefore, this expression is equivalent to Eq. [2]. When the WPNU response curve is a straight line, its slope is constant and equal to (fertilizer N uptake − control N uptake)$_{regr}$/FE. The Rel Eff index could be thought of as a straight-line approximation of the response curve (using two points: control and one fertilizer rate); therefore, it is reasonable that it was closer to the FE method in 1998 and 2000. Although not statistically different in 1999, N availability using the FE approach was almost double at the low rate and one-third at the high rate, compared with Rel Eff. This year, a curvilinear (exponential) function was chosen to describe the relationship between WPNU and fertilizer N. This model presents a steeper slope for low N rates, which asymptotically approaches zero for higher N rates. As a result, higher crop responses were assigned proportionally much higher FE values than even slightly lower responses. Given the wide range of crop N uptake values

observed for manure treatments, just a few high responses can result in an apparently disproportionately high FE estimation. If the eight observations for WPNU for the low rate in 1999 were averaged and entered into the response curve as one value, the FE would be considerably lower, resulting in a N availability of 24% instead of 43%, much closer to the Rel Eff value. This illustrates the strong influence the mathematical function chosen has on the results for the FE approach. This is perhaps a major limitation of the method, which requires that one select a specific function to describe the crop behavior. That function might change from season to season and for different crop parameters. Conversely, regression reduces the weight given to a single N rate.

The Diff Meth only compares crop responses in manured or fertilized plots to controls. This approach has limited applicability in extreme situations where assumptions might not be met, such as when the soil is either high or severely deficient in available N. When using ^{15}N-enriched manure, we positively know that excess ^{15}N in the plant was provided entirely by applied manure. The ^{15}N method does not require calibration curves and the control is the background level of ^{15}N. Although this has to be measured, the value should be equal or very close to the natural abundance of this isotope, provided that no ^{15}N-enriched material was applied. These measurements are very accurate and repeatable. The ^{15}N method provides a more precise and direct estimate of manure N use by crops. However, this method does not allow for N availability estimates per se unless ^{15}N-enriched fertilizer treatments are included.

In spite of the apparent lower accuracy of the Diff Meth, it provided virtually the same average estimate of manure N recovery estimates as the ^{15}N method. This might suggest that, at least for our experimental conditions, the Diff Meth could be the most cost-effective approach for determining manure N recovery. However, considering the breadth of the N recovery ranges, sometimes going from negative to more than 100%, it is somewhat surprising that it has worked out so well. Although using ^{15}N is costly and involves much more work, from experiment setup to sample analyses, manure N recovery measurements using this method are invariably more consistent and reliable.

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